Dynamic nuclear polarization and Knight shift measurements in a breakdown regime of integer quantum Hall effect

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Abstract

Nuclear spins are polarized electrically in a breakdown regime of an odd-integer quantum Hall effect (QHE). Electron excitation to the upper Landau subband with the opposite spin polarity flips nuclear spins through the hyperfine interaction. The polarized nuclear spins reduce the spin-splitting energy and accelerate the QHE breakdown. The Knight shift of the nuclear spins is also measured by tuning electron density during the irradiation of radio-frequency magnetic fields.

Key words: hyperfine interaction, quantum Hall effect breakdown, nuclear magnetic resonance, Knight shift
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Interplay between nuclear spins and electron spins has recently attracted great interests in the fundamental research of electron transport in low-dimensional systems [1,2,3,4]. In integer quantum Hall (QH) systems, inter-edge-channel scatterings of electrons accompanied by spin flips cause nuclear spins to polarize via hyperfine interaction[2]. In fractional QH systems near spin-polarized/unpolarized transition, the hyperfine interaction also takes part in the dynamic nuclear polarization (DNP)[1,3].

On the other hand, when electron spins are polarized, the hyperfine interaction generate an effective magnetic field for nuclear spins. As a result, nuclear magnetic resonance (NMR) frequency is shifted depending on the electron spin polarization. This frequency shift is referred to as the Knight shift. Since the Knight shift is proportional to the electron spin polarization, studies on the Knight shift revealed electron spin properties in two-dimensional electron gases (2DEGs) that had not been accessed by conventional transport measurements; for example, finite-size skyrmions[5] and domain structures with different spin configuration in fractional QH systems[6]. Thus, a new method for electrical polarization of nuclear spins and for detection of the Knight shift will have a potential to uncover novel spin-dependent phenomena in QH systems.

In this paper, we report electrical polarization of nuclear spins and all-electric measurements of the Knight shift in a breakdown regime of odd-integer quantum Hall effect. When an applied electric current exceeds a critical current I_c of QHE breakdown, electrons are

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excited to the upper Landau subband with the opposite spin polarity. The flip of electron spin S flops nuclear spin I through the hyperfine interaction, $H_{\rm hyp} = AI \cdot S = A(I^+S^- + I^-S^+)/2 + AI_zS_z$, where A is the hyperfine constant. As a result, nuclear spins are polarized along the external magnetic field $B_{\rm ext}$ ($\langle I_z \rangle > 0$). The polarized nuclear spins generate an effective magnetic field $B_{\rm NS}$ for electron spins. The $B_{\rm NS}$ reduces the spin-splitting energy $E_{\rm s} = |g|\mu_{\rm B}(B_{\rm ext} - B_{\rm NS})$, where g is the effective g-factor and $\mu_{\rm B}$ is the Bohr magneton. Thus, the DNP accelerates the QHE breakdown. Since the DNP is induced in the bulk part of the 2DEG in this method, the DNP can be utilized as a probe for Knight shift measurements in the bulk part of QH conductor.

Experiments were performed using a 20-μm-wide Hall-bar device fabricated from a wafer of GaAs/$\rm Al_{0.3}Ga_{0.7}As$ single heterostructure with 2DEG. The mobility and sheet carrier density of the 2DEG are 220 $\rm m^2$/Vs and 1.53×10^{15} $\rm m^{-2}$ at 4.2 K, respectively. Gate voltage $V_{\rm G}$ is applied to the front gate electrode to tune the carrier density of the 2DEG. All the measurements were performed in a dilution refrigerator with a base temperature of 30 mK. A single-turn coil around the device was used to irradiate radio-frequency (rf) magnetic fields.

Figure 1(a) shows the voltage-current (V_{xx}-I) characteristics at a Landau level filling factor under the gate $\nu_{\rm G} = 1.1$ ($B_{\rm ext} = 3.21$ T and $V_{\rm G} = -0.33$ V). The solid and dashed curves are respectively obtained by sweeping the current in positive and negative directions. The critical current $I_{\rm c} = 0.24$ μA in the down-sweep curve is smaller than $I_{\rm c} = 0.29$ μA in the up-sweep curve. Figure 1(b) shows the time evolution of V_{xx} at $\nu_{\rm G} = 1.1$ after switching bias current from $I = 0$ μA to 0.33 μA. The value of V_{xx} increases slowly with a long relaxation time over 500 s. After complete saturation of V_{xx} at $I = 0.33$ μA, rf-magnetic field parallel to the 2DEG is applied. The value of V_{xx} decreases at the NMR frequency of ^{75}As as shown in Fig. 1(c).

The slow time evolution in V_{xx} and the detection of the NMR signal definitely show that the nuclear spins are dynamically polarized in the QHE breakdown regime, similar to our earlier work using different devices without gate electrode[7]. The shift of $I_{\rm c}$ toward the smaller-current side in Fig. 1(a) and the increase in V_{xx} in Fig. 1(b) indicate the acceleration of the QHE breakdown by the DNP, which can be understood by the reduction of the spin-splitting energy $E_{\rm s}$. These results show $\langle I_z \rangle > 0$.

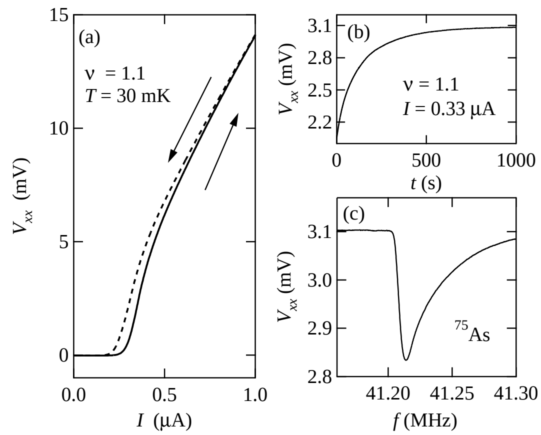

Fig. 1. (a) V_{xx}-I characteristics at $\nu = 1.1$ taken by sweeping current in positive (solid) and negative (dashed) directions. (b) Time evolution of V_{xx} after switching current from $I = 0$ to 0.33 μA at $t = 0$. (c) NMR spectrum for ^{75}As detected by measuring V_{xx}.

Let us turn our attentions to the Knight shift measurement. Recently all-electric detection of the Knight shift was demonstrated using QH edge channels[8]. We employed a similar technique to measure the Knight shift in the bulk part of the QH system. First, nuclear spins are polarized at $\nu_{\rm DNP} = 1.1$ ($B_{\rm ext} = 3.21$ T) by applying pumping current $I_{\rm pump} = 0.33$ μA. Next, the current is turned off and the fillng factor is set to $\nu_{\rm rf}$ by changing $V_{\rm G}$. Then, the rf-magnetic field with a frequency f is applied for 5 sec. Finally, the filling factor is set back to $\nu_{\rm DNP} = 1.1$ and the time evolution of V_{xx} is recorded. By repeating the above procedure with different f, an NMR spectrum (V_{xx}-f curve) is obtained.

We carry out the above procedure at various $\nu_{\rm rf}$ between $\nu_{\rm rf} = 0$ and 2, and the NMR spectra of ^{71}Ga are obtained as shown in Fig. 2. The NMR frequencies are different from each other depending on $\nu_{\rm rf}$. In the case of $\nu_{\rm rf} = 0$ (depletion), the nuclear spins are not affected by electron spins. Therefore the NMR frequency for $\nu_{\rm rf} = 0$ is equal to the intrinsic NMR frequency of ^{71}Ga without Knight shift. In the cases of $\nu_{\rm rf} \neq 0$, the NMR frequencies depend on the electron spin polarization because the nuclear spins interact with electrons in QH states of $\nu_{\rm rf}$ during rf-field application. In the NMR spectrum for $\nu_{\rm rf} = 0.99$, where the electron spins are fully polaried, the resonance dip appears at f

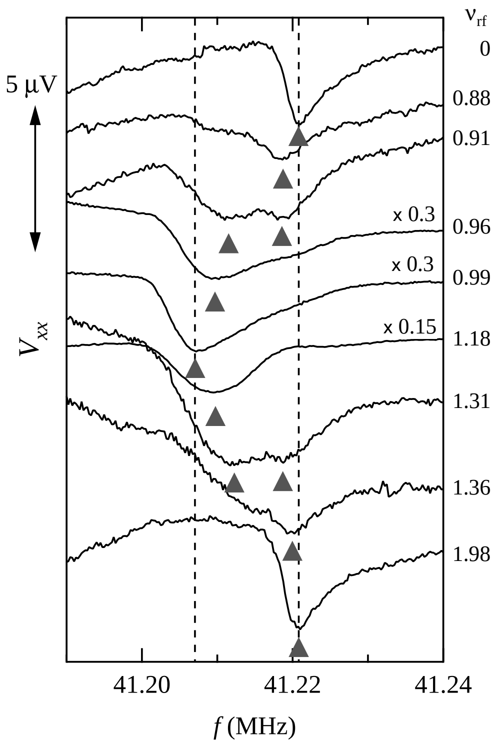

Fig. 2. NMR spectra taken by applying rf-magnetic field at various filling factors between 0 and 2. The positions of the dips are indicated by triangles. The dashed lines show NMR frequencies for $\nu_{\mathrm{rf}} = 0$ and 0.99. The traces are shifted vertically for clarity.

= 40.2067 MHz. The frequency gives the largest shift 14.3 kHz from the NMR frequency $f = 40.2210$ MHz for $\nu_{\mathrm{rf}} = 0$. In the spectrum for $\nu_{\mathrm{rf}} = 1.98$, where both up-spin and down-spin subbands of the lowest Landau level are equally occupied, the Knight shift of the NMR frequency is almost zero. We infer that the values of the Knight shift are reasonable as compared with the Knight shift reported in earlier works[5,6,8].

At intermediate filling factors $\nu_{\mathrm{rf}} = 0.91$ and 1.31, the NMR spectra exhibit double-dip structures. The higher frequency dips appear at frequencies close to the NMR frequency for $\nu_{\mathrm{rf}} = 0$. The NMR spectra with two resonant frequencies recall the "dispersive-line-shape spectrum" observed in quantum Hall states near $\nu =$ 0.9 and 1.1[9,10]. Although the physical interpretation of the double-dip structure is not known yet, it suggest the coexistence of electron systems with different spin polarization.

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